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Force Plate Balance Response of Seafarers during Still and Rough Sea Conditions

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***Abstract*—Seafarers are constantly exposed to varying ground reaction forces due to extreme weather conditions. These forces may lead to the progression of osteoarthritis and musculoskeletal injuries. The ground reaction forces of 18 subjects were measured, with Advanced Mechanical Technology Incorporation's force plate, during still and rough sea conditions. In this study, each subject's weight factor and Sway Index is compared for different test conditions. Weight factors varied between 1.46 and 0.66 of the normal body weight. A subject's Sway Index measured during rough conditions is more than double their Sway Index measured during still conditions. It was noted that more than 70% of the subjects' Sway Indexes were greater when facing the side of the ship as opposed to the front, during still and rough conditions. Body movement and postural response is increased in order to keep the body upright during rough sea conditions as opposed to still conditions. The long term effects caused to body joints, as a result of constant exposure to varying ground reaction forces, can be determined using the measured results.**

***Index Terms*—balance, force plate, seafarers, sway index.**

I. INTRODUCTION

Ships operating at sea are manned by seafarers holding a variety of professions and ranks on board. These seafarers often spend months at sea exposed to extreme weather conditions and large swells. They are therefore constantly exposed to pitching and rolling motions in the environment in which they work and rest. In a recent discussion with captains from the South African Navy, many complained of knee and hip pain [1]. They believe this is as a result of spending a life time (20-30 years) on-board ships. During heavy swells, the ship pitches and rolls, causing the body to experience gravitational forces in various directions. The body's center of weight vector, therefore varies, causing the vertical ground reaction vector on the feet to fluctuate as well. This causes the loads on all the joints, and in particular the load on the knee and hip joints, to change from a tensional to compressional force depending on the frequency and size of the swell.

In 1999, research was done on the rough conditions Olympic Yacht racing team sailors were exposed to. Reference [2] attempted to quantify the physical demands on the sailors' knees and hips. The method was however only accurate if the sailor kept his feet equidistant on the hiking strap. Reference [3] conducted a similar study to investigate the peak moments about the knee by measuring knee extensors and flexors during sailing. Both studies found that the physical demand on the knees is especially substantial and that the applied forces are marginally close to a sailor's predicted maximal voluntary contractions.

Although navigation on large vessels does not demand the same physical activities as sailing a yacht, the seafarers are still exposed to rough sea conditions, often for much longer durations. The aim of this study was to measure the ground reaction forces which a seafarer's body experiences while at sea. These forces can give an indication of what conditions the body is exposed to and what potentially harmful contribution it has to knee and hip injuries. The study further investigates how a person's ability to balance is affected during rough seas.

A scientific hypothesis posed by [4], used psychophysical load estimation as a method to establish capacity threshold guidelines for physical task demands and their acceptable physical forces. Excessive or abnormal loading across the lower extremity joints have been linked to the progression of osteoarthritis (OA) and musculoskeletal injuries [5]. Research done by [6] suggests that certain levels of lifelong knee and hip joint forces can aggregate or increase the risk factor for developing OA. OA causes stiffness and chronic pain due to changes in the bone underneath the cartilage [7] .It is a degenerative joint disease and can be characterized by chronic degradation of hyaline articular cartilage [5]. The application and release of the high levels of compression forces on the cartilage may require a prolonged duration for proteoglycan synthesis rates to return, which can alternatively lead to cartilage cell death [8]. Cartilage is a living tissue, and therefore the threshold, at which it fails, either from mechanism of fatigue or too high stress levels, is dependent on the prevalent stress arising in a joint [9].

II. EXPERIMENTAL DATA

The reaction forces of the subjects were measured using an Advanced Mechanical Technology Incorporation (AMTI) OR6-7-1000 standard size force plate designed for static and gait studies. A total of 18 subjects were each tested on four occasions. Informed consent was obtained from each subject before any tests were conducted. Each test measured the forces in the *X*, *Y*,

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and *Z* direction and the moments in the *X, Y*, and *Z* direction as shown in Fig. 1. AMTI's MiniAmp signal conditioner and amplification were used to digitize the readings from analog to a 12 bit digital format.

The AMTI MiniAmp has a standard anti-aliasing low pass filter, 1000 Hz cutoff, for each channel. All test readings were sampled at 50 Hz, 50 samples per second, for a period of 60 seconds, resulting in 3000 force and moment measurements in each direction. The force plate was calibrated before the tests were conducted.

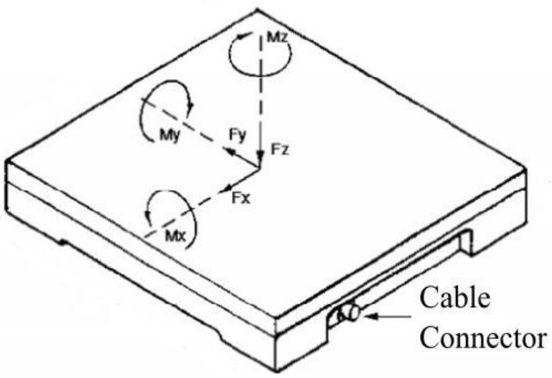

Figure 1. Force plate axes and direction of the forces and moments measured.

TABLE I. THE MAIN DIMENSIONS OF THE S.A. AGULHAS II.

Dimension	Quantity
Beam	21.7 meter
Draught, design	7.65 meter
Length, bpp	121.8 meter
Deadweight at design displacement	5000 ton
Average service speed	14 knots

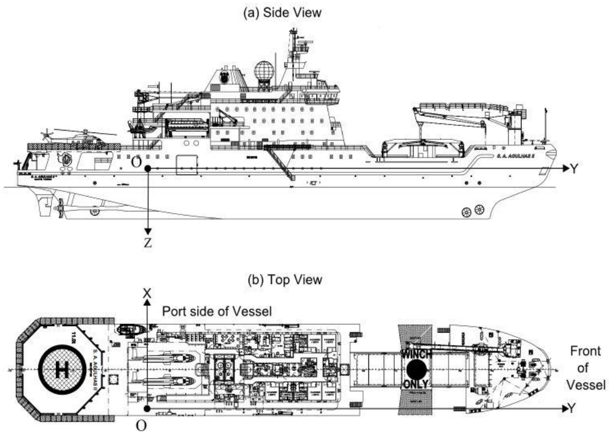

Figure 2. Scaled drawing of the vessel and the test location of data recordings indicated as "O".

The measurements were performed on-board the S.A. Agulhas II Polar Supply and Research vessel, built by STX Finland at the Rauma Shipyard and entered service in April 2012. The purpose of the ship is to support the South African National Antarctic Expedition (SANAE IV) base on the Antarctic continent [10]. She was therefore built to Polar Ice Class PC 5 with a comfort class notation of COMF-V(2)C(2) as classed by Det Norske Veritas (DNV). She is equipped with laboratories which are used for conducting scientific research in the Southern Ocean. She is utilized to carry cargo, bunker oil, helicopter fuel and passengers. Fig. 2 shows a scaled drawing of the ship. Table I contains the main dimensions of the S.A. Agulhas II and the service speed.

III. METHODOLOGY

A total of 18 healthy subjects (range: 21 years to 45 years), 8 males and 10 females, were tested on-board the S.A. Agulhas II on the 2013-2014 Antarctic voyage. Each subject was tested twice during still conditions and twice during rough conditions. Still conditions refer to conditions on-board the ship when it was stationary against an ice wall with no swell present. Rough conditions refer to when the vessel was in open seas with swells greater than 6 meters. All measurements were conducted in the starboard operations laboratory on deck 3, as indicated in Fig. 2.

Tests were conducted one subject at a time. Each subject was instructed to stand normally on the force plate, facing the front of the vessel. A 60 second measurement was performed without the subject leaving the force plate. The subject was then instructed to reposition themself on the force plate to face the port side of the vessel. A second measurement was then repeated, again without the subject leaving the force plate. The same test procedure was followed during rough conditions, first facing the front and thereafter the port side of the vessel. Tests were repeated in cases where the subject lost their balance and inadvertently stepped off the force plate.

A. Ground Reaction Forces

The ground reaction force is known as the force which acts on the foot to keep a subject pastorally upright and stable during unsupported standing [11]. This three-dimensional force vector consists of two shear components (F_x and F_y) acting along the support surface and a vertical component (F_z) acting perpendicular to the support surface as shown in Fig 1. The resultant ground reaction force *R*, is calculated using (1),

$$R_n = \sqrt{{F_{x,n}}^2 + {F_{y,n}}^2 + {F_{z,n}}^2} \qquad (1)$$

where F_x, F_y ,and F_z represents the measured forces in the *X, Y,* and *Z* direction respectively of the n^{th} sample measurement in time. The resultant ground reaction forces measured during rough conditions are compared to the resultant ground reaction forces measured during still conditions as shown in (2),

$$WF = \frac{R_{n,rough}}{R_{n,still}} \qquad (2)$$

where *WF* is the weight factor. The weight factor signifies the comparison of the resultant ground reaction force measured during still and rough conditions. It gives an indication as to how a subject's weight is varied and how much extra force is applied to the joints during rough conditions as opposed to still conditions.

B. *Balance Measurements*

Human balance is the ability to maintain the body upright in an equilibrium position by moving the center of gravity (COG) over the base of support [12]. Balance can either refer to postural steadiness, i.e. static, or postural stability, i.e. dynamic. Postural steadiness captures the characteristics of postural sway during quiet standing. Postural stability characterizes the postural response of the body as a result of an external perturbation [13]. The ability to maintain balance during still conditions around the vessel is characterized as postural steadiness and the ability to maintain balance during rough conditions is characterized as postural stability. In both cases the Sway Index (SI) can be used to quantify a person's ability to balance [14]. The SI gives the average of the sway movement during a test. Thus, it calculates the average speed at which the resultant ground reaction force changes its location. The location of the resultant force in the X and Y coordinates (COP_x and COP_y) are calculated using (3) and (4) respectively.

$$COP_{x,n} = \frac{M_{y,n}}{F_{z,n}} \tag{3}$$

$$COP_{y,n} = \frac{M_{x,n}}{F_{z,n}} \tag{4}$$

M_x and M_y represents the measured moments in the X and Y axes respectively as shown in Fig 1. The SI for a 60 second test of n = 3000 samples is calculated as:

$$SI = \frac{\sum_{i=1}^{n-1} \frac{\sqrt{(COP_{x,i+1} - COP_{x,i})^2 + (COP_{y,i+1} - COP_{u,i})^2}}{\Delta t}}{(n-1)} \tag{5}$$

A sample measurement is taken every 20 milliseconds (Δt = 0.02 seconds).

IV. RESULTS

The results of the measured ground reaction forces (which seafarers, working on vessels, are exposed to due to rough sea conditions) are presented below. Investigations into how the seafarers' ability to balance is affected are also presented. A total of 72 successful tests were performed.

Fig. 3 shows how the weight factor of a random chosen subject fluctuates over a period of 60 seconds. This indicates that the ground reaction force, and therefore the forces in the knee and hip joints, varied between 1.23 and 0.86 times the normal force between calm and rough conditions. Fig. 3 shows a varying sinusoidal waveform as a result of steady rolling and pitching of the boat with no harsh judders or slams present.

The box plot in Fig. 4 gives the distribution of the weight factor of all the measured results. The maximum and minimum weight factors measured were 1.46 and 0.66 respectively. Thus, the ground reaction forces acting on the body through the feet can increase up to 1.46 times the weight of the body, resulting in extra strain on the joints. The cyclic nature of the applied force can lead to possible fatigue in the cartilage.

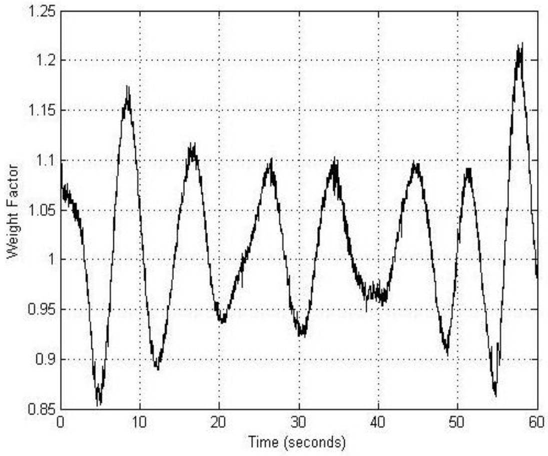

Figure 3. Weight factor changes over a period of 60 seconds.

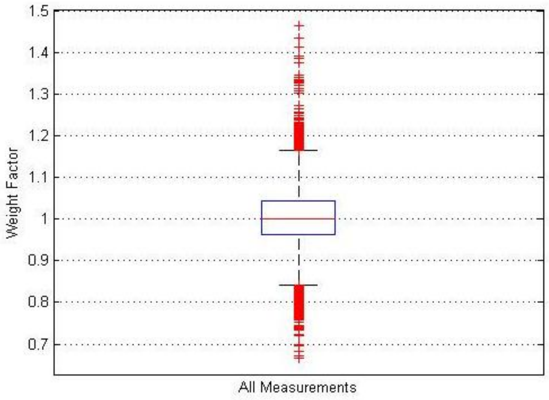

Figure 4. Weight factor distribution of all subjects.

To keep the body upright, the COP changes constantly. Fig. 5 compares a randomly chosen subject's COP displacement during still conditions, opposed to that of rough conditions, while facing the front of the vessel. The COP is shifted around much more frequently at greater speeds and is distributed on a much greater surface area during rough conditions. It shows that the body sways to a greater extent to keep itself in an upright position during rough conditions.

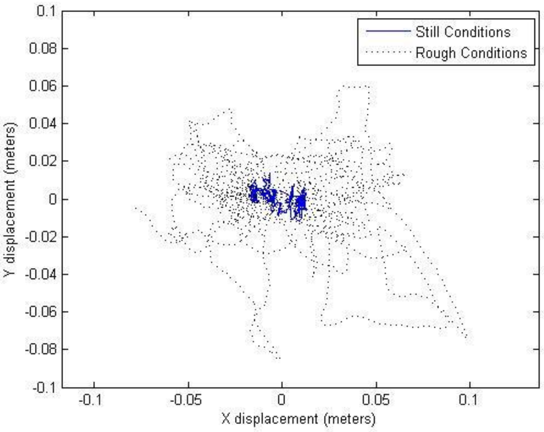

Figure 5. COP plot of still and rough sea conditions.

Each test's SI was calculated using (5). A bar graph, showing each subjects' SI, for all four tests, is displayed in Fig. 6. The results show that each subject's SI for the tests done during still conditions, are similar. For the majority of the subjects, the SI tested during rough conditions is also in close proximity. However, there is a noticeable difference when comparing each subject's SI tested during still and rough conditions facing the front and the port side of the ship. All the subjects' SI during rough conditions is more than double that of still conditions. On closer observation, it was noted that more than 70% of the subjects' SI is greater when facing the port side of the ship, both during sill and rough conditions.

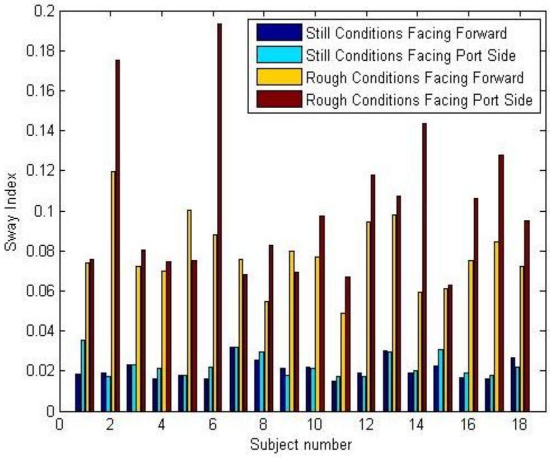

Figure 6. Each subject's SI for the four different test conditions.

The box plot in Fig. 7 compares the SI of the four different test conditions. During still conditions the SI results are very similar; however, the mean and maximum SI is greater when facing the port side of the vessel. During rough conditions, the mean and maximum SI is also greater when facing the port side of the vessel. The ship's length is much longer than the wavelength of the periodically oncoming waves, and therefore has smaller pitching moments. The breadth however, is usually similar or smaller than the wavelength of the oncoming waves, causing the ship to have larger rolling moments in the troughs of the waves.

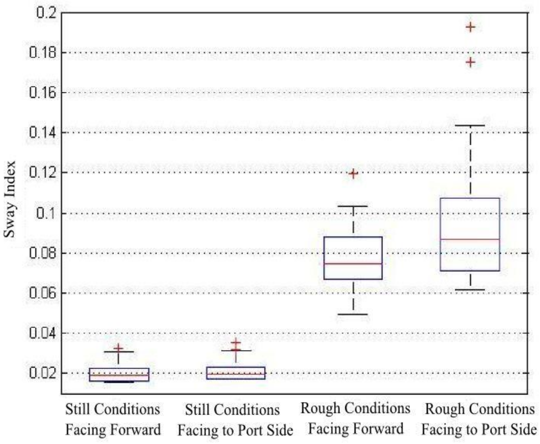

Figure 7. Box plot comparing the SI of the different test conditions.

The SI for either facing the front or port side of the vessel is far greater during rough conditions when compared to still conditions, with a mean still-front to rough-front factor of 4 and a still-port to rough-port factor of 4,4. This shows that more frequent, faster reactions and greater body sway activity is required to keep the body upright during rough conditions; compared with still conditions.

V. CONCLUSION

The study showed that the body experiences a fluctuation in ground reaction forces during rough sea conditions. Resultant forces with a maximum of up to 1.46 and minimum of 0.67 times the body's normal weight was measured and is characterized by a so called weight factor. The subjects' SI during rough conditions is more than double the SI during still conditions. Seafarers therefore require more body activity and joint movement to keep them upright. Further research can be done to investigate the effects this might have on the body and whether this increase in body activity and extra forces aggregate the development of OA. Thresholds or guidelines can be established to show long term effects caused to the body. The damage caused to the knee and hip joints, due to the frequency and amplitudes of the measured ground reaction forces, needs to be determined.

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